

Three Conservation Applications of Astronaut Photographs of Earth: Tidal Flat Loss (Japan), Elephant Impacts on Vegetation (Botswana), and Seagrass and Mangrove Monitoring (Australia)

JULIE A. ROBINSON^{1,6}, KAMLESH P. LULLA¹, MINORUKASHIWAGI², MAGGIE SUZUKI², M. DUANE NELLIS³, CHARLESE BUSSING^{4,7}, WARREN J. LEELONG⁵ AND LEN J. MCKENZIE⁵

¹Office of Earth Sciences, Johnson Space Center, National Aeronautics and Space Administration, 2400 NASA Rd 1, C23, Houston, TX 77058, U.S.A.

²Tokyo Office, Japan Wetlands Action Network, 3-18-1 #105, Higashi-Toyoda, Hino-shi, Tokyo 191, Japan

³Department of Geology and Geography, and Eberly College of Arts and Sciences, West Virginia University, P.O. Box 6286, Morgantown, WV 26505, U.S.A.

⁴Geography Department, Kansas State University, Manhattan, KS 66506, U. S. A.

⁵Northern Fisheries Centre, Queensland Department of Primary Industries, P.O. Box 5396, Cairns, Qld 4870, Australia

Footers:

⁶*Lockheed Martin Operations Support, email julie.a.robinson1@jsc.nasa.gov*

⁷*Retired*

Number of words in document: 4705

Outside RH: Conservation Data from Orbital Photography

Inside RH: *Robinson et al.*

Send correspondence to:

Julie A. Robinson
Lockheed Martin Operations Support
2400 NASA Road 1, C23
Houston, TX 77058

Phone: 281-483-5582
FAX: 281-483-2911
email: jarobins@ems.jsc.nasa.gov

Abstract: NASA photographs taken from low Earth orbit can provide information relevant to conservation biology. This data source is now more accessible due to improvements in digitizing technology, Internet file transfer, and availability of image processing software. We present three examples of conservation-related projects that benefited from using orbital photographs. (1) A time series of photographs from the Space Shuttle showing wetland conversion in Japan was used as a tool for communicating about the impacts of tidal flat loss. Real-time communication with astronauts about a newsworthy event resulted in acquiring current imagery. These images and the availability of other high resolution digital images from NASA provided timely public information on the observed changes. (2) A Space Shuttle photograph of Chobe National Park in Botswana was digitally classified and analyzed to identify the locations of elephant-impacted woodland. Field validation later confirmed that areas identified on the image showed evidence of elephant impacts. (3) A summary map from intensive field surveys of seagrasses in Shoalwater Bay, Australia was used as reference data for a supervised classification of a digitized photograph taken from orbit. The classification was able to distinguish seagrasses, sediments and mangroves with accuracy approximating that in studies using other satellite remote sensing data. Orbital photographs are in the public domain and the database of nearly 400,000 photographs from the late 1960s to the present is available at a single searchable location on the Internet. These photographs can be used by conservation biologists for general information about the landscape and in quantitative applications.

Introduction

In a guiding document on conservation research for development agencies, the U.S. National Research Council (1992:5) noted that "Additional research and technical development are needed to advance the utility of remotely sensed data for ecosystem monitoring in developing countries." Since that time, technical expertise and availability of remote sensing and GIS as

tools for monitoring and conserving biodiversity have spread widely throughout the developed and developing world.

Conservation biologists need remote sensing data that provide multiple observations of the same area over time, are at suitable spatial resolution, and can be linked with ground observations. The most common remote sensing data sources currently in use are from automated satellites—Landsat, AVHRR (Advanced Very High Resolution Radiometer), IRS (India Remote Sensing) or SPOT (Le Système Pour l'Observation de la Terre). If a research question requires purchasing and analyzing multiple images, data acquisition can be prohibitively expensive. Recent data from Landsat or SPOT are expensive because they are distributed at cost of acquisition, and all the users share the cost of operating the satellite and distributing the data (Paulsson 1992; although the cost structure was reduced significantly for Landsat-7 images). Data fully available in the public domain, such as AVHRR, are at coarse resolution (scale 1 pixel = 1 km²) and unsuitable for studies of smaller areas.

✓ A lesser-known and underused source of remote sensing data are the Earth-looking photographs taken by astronauts from low orbit (Wobber 1969; Helfert & Lulla 1989; Lulla et al. 1996; Nedeltchev 1999). The photographs are available in the public domain at cost of reproduction. The nearly 400,000 images taken to date are cataloged in a database that can be searched via the World Wide Web and low-resolution browse images are also available (Office of Earth Sciences 2000). Astronaut photographs differ from automated satellite data in several ways. (1) The data set begins with the early Mercury missions in the 1960s, far earlier than the automated satellites, and continues to the present. (2) The data is photographic rather than collected using multispectral scanners. Photographs are usually taken with film cameras ranging from 35-mm to 241-mm formats (a 70-mm format camera with 55 × 55 mm image size has been used for the majority of photographs). Most photographs are taken using color positive film, but black and white, spectral bandwidth filters, and false color infrared have also been used. Before using a computer for image processing, photographs must be digitized to create three bands (red, green, blue). (3) Because they were taken by humans out the windows of

spacecraft and with several different lenses, the photographs are much more variable in angle and scale than the automated data. If an image is to be incorporated into a geographic information system (GIS), it must be georeferenced by the user. (4) Unlike commonly used satellite data, photographs are taken at a wide variety of solar angles. Variable illumination can accent topographic, geological, vegetative or cultural features, but also makes quantitative comparisons of reflectance at a given location more challenging. Variations in date, time, look angle, and illumination also make the creation of an image mosaic difficult, except when done with photographs taken seconds apart.

We present three applications to illustrate types of information that can be obtained from astronaut photographs and how that information can contribute to conservation projects. By introducing this tool to conservation biologists, and providing examples of the ways that astronaut photography has contributed to larger projects, we hope that it will benefit other ongoing research activities. First, we examine the ability of a photograph to qualitatively illustrate broad areas of wetland change using comparative photographs of Isahaya Bay, Japan, before and after the diking of a 3000 ha tidal mudflat. Second, we illustrate the use of astronaut photography to detect vegetation stress caused by dense elephant populations in Botswana. Finally, we present the results of supervised classification of a digitized photograph of Shoalwater Bay, Australia, for identifying seagrass meadows.

Documenting Wetland Loss in Isahaya Bay, Japan

To test the potential for rapid environmental assessment using shuttle photographs, we wanted to identify and follow a large wetland area that was (1) known to be of importance to migratory waterbirds (e.g., qualified to be listed on the Ramsar List of Wetlands of International Importance, Frazier 1999, or in one of the regional Shorebird Reserve Networks) and (2) subject to an immediate catastrophic threat. By referring to newspaper articles and press releases from the Japan Wetlands Action Network (JAWAN) we identified two such areas in Japan: Isahaya Bay

(32.9° N 130.2° E) in the Ariake Sea (Ariakekai) near Nagasaki and Fujimae tidal flat (35.0° N 136.9° E) near Nagoya City.

Plans to reclaim these areas of tidal mudflats have been the subject of activism by Japanese and international nongovernmental conservation organizations (NGOs, including JAWAN and World Wide Fund for Nature) opposed to destruction of the few remaining tidal flats in Japan. Based on use by migratory waterbirds, activists consider these tidal flats to be important links in the chain of wetlands used by migratory waterbirds in the East Asian-Australasian Flyway (flyways in the region described by Anonymous 1996). Another concern was the use of Isahaya Bay by species of conservation concern such as endangered Saunder's Gulls (*Larus saundersi*) which winter in the area, and a local mud skipper (*Boleophthalmus pectinirostris*) which is classified as vulnerable. At Isahaya Bay on 14 Apr 1997, 293 steel slabs completed a dike that cut off approximately 3000 ha of tidal flats from the rest of the Ariake Sea. In contrast, the proposal to reclaim the area of Fujimae tidal flat was still under consideration by the Aichi Prefecture (Suzuki 1998).

We added these sites as photographic targets during real-time mission operations (cf. Reilly et al. 1998) for the STS-90 crew during April 1998. After photographs of the two areas were returned from the mission, we also identified a reference photograph prior to the diking of Isahaya Bay by searching the online database of astronaut photographs posted to the World Wide Web (Office of Earth Sciences 2000). Photos were digitized from 2nd generation film (copied from a master made from the original) at 2400 pixels/in using a flat-bed scanner. Non-GIS-based image processing for the Isahaya Bay photos was conducted using PhotoShop (version 4.0, Adobe Systems Inc., Mountain View, California) to rotate, rescale and align the two images for optimal visual comparison.

Two comparative photos for Isahaya Bay are shown in Figure 1. In the 1989 photograph (left), the shallow area (arrow) appears similar to the deeper bay, with subtle tan colors in the water suggesting the presence of either sediments or inundated mudflats. The dike can be seen in the April 1998 photograph (right) as an unnaturally sharp boundary (arrow) between the blue

of the bay and the extremely uniform light-colored region that has been separated from it. The former tidal flat appears almost white because the mud flat has been isolated from tidal action and salts have been exposed by extended evaporation.

This visual pattern of sharp boundaries and high reflectance would appear similar in remote sensing images from other satellites if bands were selected and displayed to approximate red, green, and blue color. Although different for each image, the spatial resolution of the two images used is superior to Landsat Thematic Mapper (TM, 30 m/pixel). The 1989 image has a digital spatial resolution of 9-13 m/pixel (calculated based on a 326 km altitude, 250 mm lens, 55 mm original image size, and 50 line-pairs/mm film resolving power) and the 1998 image has a digital spatial resolution of 17-25 m/pixel (calculated based on a 246 km altitude, 100 mm lens, 55 mm original image size, and 50 line-pairs/mm film resolving power).

Astronauts were able to respond to real-time information from the ground and take the requested photograph. The database of previous photographs was robust enough to find a comparative photograph showing the original state of Isahaya Bay, even though this had not been a specific target for previous missions.

This application is an example of how orbital photographs can be a valuable source of public information relevant to conservation issues. The photographs in Figure 1, along with a photograph of the Fujimae tidal flat area (electronic still camera image S90e5239, not shown here) were used at public hearings in Japan (Atsuo Tsuji, pers. comm.) to illustrate the magnitude of tidal flat loss, and have since been used in articles about tidal flat protection in Japan (Kashiwagi 1998). The example of the visible change in Isahaya Bay was presented at the same time as local governments were evaluating plans to reclaim other tidal flats. For example, after receiving a large amount of public comment, Takehisa Matsubara, Mayor of Nagoya, officially declared that the city would abandon a proposed landfill project at the Fujimae Tidal Flats and apply to have the area listed in the Ramsar Convention on Wetlands (8 February 1999; Atsuo Tsuji, pers. comm.).

Identifying Elephant Impacts on Vegetation, Botswana

As a side project accompanying construction of detailed landuse and land cover maps for Botswana (Coleman et al. 1996), we sought a method for estimating locations where African Elephants (*Loxodonta africana*) were having impacts on the vegetation at scales relevant to mapping and park management. The area of interest was Chobe National Park, Botswana (18.5° S 24.5° E). This area has robust and increasing elephant densities (ca. 50,000 - 80,000; Nellis et al. 1990; Ben-Shahar 1993; Herremans 1995) that impact Zambezi teak (*Balklaiea plurijuga*) and associated forest species. The impacts of expanding elephant populations on woodland vegetation are of concern (e.g., Ben-Shahar 1993, 1996a, b; Herremans 1995), particularly to local land managers and national conservation planners seeking a sustainable balance between wildlife populations and natural vegetation.

After a thorough search of the NASA Astronaut photography database, we selected one orbital photograph to demonstrate the use of this imagery in vegetation stress detection (NASA photograph STS008-33-993; Figure 2, top). The photo shows part of the study area south of the Chobe River just west of the confluence with the Zambezi River. It was taken on 5 September 1983, during local spring and just before onset of the rainy season. We took this image into the field in 1989 for preliminary assessment, conducted image analysis in 1989 (Nellis et al. 1990), and then conducted qualitative field validation during three trips 1990-1994.

A portion of the photo was video digitized to 512 x 512 pixels (30 pixels = 20 km, or 667 m/pixel) with three color bands (red, green, blue). This spatial resolution is far less than the photographic or maximum digital resolution of approximately 24-35 m/pixel (calculated based on a 353 km altitude, 100 mm lens, 55 mm original image size, and 50 line-pairs/mm film resolving power). Our subsequent analyses used an ERDAS image analysis system. We identified six landscape types using an unsupervised cluster analysis and the multiple pass isodata routine (Figure 2, bottom). Based on additional information on soil and topographic position (Coleman et al. 1996), these vegetation units represented six classes: river, riparian/tall grass, elephant

impacted area, marginal grass/woodland, medium density teak woodland, and high density teak woodland. The classes follow sequentially from bare soil near the Chobe River (lightest areas in Figure 2) to increasingly dense vegetation, to dense woodlands at higher elevations and greater distances from the river. Lighter areas near the water corresponded to known areas of intense elephant impact.

We extracted additional information about the spatial variability in contrast in different parts of the image using textural analysis (defined by Russ 1995:259-262, used similarly to examine vegetation heterogeneity by Briggs & Nellis 1991). We first used a density slicing technique to examine the gross pattern of variation in the different bands. The red band generated the greatest degree of variation across the image, so we used it for subsequent analyses. Empirical selection of the red band for texture analysis is supported by spectral analysis for other remote sensing studies of vegetation in Botswana. Ringrose et al. (1990, 1999) determined that increases in reflectance indicating increased amounts of exposed soil were best measured using the red band (Landsat MSS2 or TM3, roughly corresponding to the red band in this digitized photograph) and near infrared (not recorded by the film used for this photograph). Functionally, the red band corresponds to the region of chlorophyll absorbance.

We measured texture by sequentially examining the range of values in the red band within a 3 pixel x 3 pixel window. We first determined means and standard deviations for red-band textural values for each of the major landscape units of the Chobe District that had been identified by the unsupervised classification. The higher the textural value, the greater the degree of contrast in the landscape unit. We then compared the contrast in various parts of the image with these means to identify patchiness. The mean textural values were similar throughout the photograph (Nellis et al. 1990). However the standard deviation was greater for areas we believed to be elephant impacted than for other woodland vegetation classes (elephant area SD = 24, high density woodland SD = 7, marginal grass/woodland SD = 3). The difference in standard deviation makes functional sense based on the behavior of elephants. Elephants concentrate in areas based on accessibility to water. In the areas of concentration,

vegetation damage is highly variable and irregular in pattern (Ben-Shahar 1993). This variable vegetation damage corresponds to the irregular patchiness identified from the astronaut photograph.

A team of field scientists who were field validating a number of GIS products (Coleman et al. 1996), took both the original astronaut photo and the classified image to Botswana during several field campaigns (1990-1994). They qualitatively verified the vegetation classes and the location and conditions of areas identified as potentially impacted by elephants. Elephant impacts were greater near permanent water sources (see also Ben-Shahar 1993; Verlinden & Gavor 1998) near the Chobe river (Figure 2, a). Locations (b) and (c) indicated areas of elephant impact identified away from water. Qualitative verification results indicate that the astronaut photography was able to detect vegetation impacts caused by elephants in this habitat.

A useful extension of the analyses presented would be to add the texture measure to the three original bands (red, green, and blue) as a fourth band and then recluster the data. Such an approach should improve the ability to identify elephant damaged areas and distinguish them from similar but undamaged vegetation. Furthermore, a quantitative accuracy assessment is needed to fully establish the use of texture analysis with astronaut photography. Unfortunately, project constraints prevented additional analyses or quantitative field verification. However, we believe that our qualitative verification is sufficient to justify the use of this analysis technique for studies of other large-scale vegetation disturbances.

Remote Sensing of Seagrass Beds, Shoalwater Bay, Australia

Submerged aquatic vegetation can serve as an indicator for coastal environmental monitoring (Dennison et al. 1993). Seagrasses are important ecological indicators because they support coastal fisheries productivity, stabilize sediments to maintain water clarity (which links them to coral reef health), and support marine endangered species such as sea turtles and dugongs (Hatcher 1989; Lee Long et al. 1996). Landsat data and aerial photographs have been used to

differentiate seagrass meadows from sandy bottom areas and to monitor change (e.g., Ferguson et al. 1993; Luczkovich et al. 1993), and we tested whether orbital photographs could serve similar purposes.

Our objective was to see if astronaut-acquired photographs could be used for seagrass and mangrove identification. We studied seagrass meadows in Shoalwater Bay, tropical Queensland (22.5° S 150.3 E). We chose this site because a seagrass map had already been compiled from detailed field surveys, and an orbital photograph we considered suitable for classification was available (250 mm lens, near vertical look angle, and sharp focus; STS51D-45-63, April 1985). The photograph was digitized from 2nd generation film at 2400 pixels/in using a flatbed scanner. Georeferencing was performed using ERDAS Imagine software (version 8.3). We registered the digitized image to a base map (Lee Long et al. 1996) by developing a 1st-order polynomial model with a minimum of 20 tie points that were identifiable in the image and on the map. We first chose three ground-control points uniformly arrayed around the bay. Additional ground-control points were selected to be uniformly distributed in and around the bay, with root mean square error (RMS error) and total RMS error determined incrementally as each point was added (ERDAS 1997; examples in McRay et al. 2000; Robinson et al. 2000). Final total control point error was 4.1643 pixels. The scale of the resampled image was reduced to match the map. Before resampling the image to register it to the map, each pixel in the digitized image represented approximately 17 m × 17 m on the ground (calculated based on a 417 km altitude, 250 mm lens, 55 mm original image size, and digitized at 2400 pixels/in); after registration, the image conformed to map pixel sizes of 143 m in width.

The georeferenced image was then exported for classification using MultiSpec (PC-based) freeware (Landgrebe & Biehl 1997). We identified six habitat classes based on references to a map of seagrass habitats constructed using diver-based field surveys (Lee Long et al. 1996, 1997): seagrass, land, water, clouds, sediment, and mangrove. We chose a total of 115 training fields, encompassing 26479 pixels, and 43 test fields encompassing 6528 pixels, and performed maximum likelihood classification. Class performance was estimated by

the resubstitution method and given in terms of percent accuracy for each class, overall percent accuracy, and an overall Kappa Statistic (the proportional reduction in error generated by a classification process compared with the error from a completely random classification, Congalton 1991).

The georeferenced photo of Shoalwater Bay is shown in Figure 3. A relatively simple supervised classification was able to correctly identify the majority of pixels (Table 1). Clouds and water could be distinguished and eliminated from consideration with > 93% accuracy based on test fields. When the entire image was analyzed, mangroves were commonly misclassified as upland areas (Table 1). We repeated the analysis after eliminating upland areas in the reference map (a shoreline mask) and identification improved from 59.8% to 93.5 % accuracy based on test fields.

The greatest challenge in the image classification was distinguishing shallow turbid (sediment-heavy) waters from seagrass beds. When the entire image was classified, seagrasses were identified with relative high accuracy (84.3% based on test fields) but were also frequently misclassified as sediments (12.7% based on test fields, Table 1). However, sediments were not well identified (11.3% accuracy based on test fields) and were often misclassified as seagrasses (85.1% based on test fields). A likely explanation for the difficulty in identifying shallow areas that did not contain seagrass meadows rests in the way that we combined all seagrass species into a single category. More sparsely growing seagrasses are very unlikely to be distinguishable from sediments in an image taken from orbit (see images of Shoalwater Bay seagrass meadows in Lee Long et al. (1997). In the analysis using the shoreline mask, seagrass classification accuracy actually declined while sediment classification accuracy improved to 61.7% based on test fields (Table 1).

The next stage of the seagrass analysis will be to repeat the study using the full-resolution seagrass GIS developed from diver-based field transects. In the reanalysis, predictions about which seagrass communities form meadows that would be identifiable from orbital imagery will be tested. The GIS-based analysis will have the further advantage of better

preserving the resolution present in the original image before georeferencing. Using an image acquired closer to the date of the field surveys would also likely improve classification accuracy.

Discussion

Orbital photographs have the potential to contribute to a range of conservation applications from qualitative image interpretation to quantitative remote sensing analysis. They provide a visual context for large-scale environmental changes in a way that is easily communicated to the public. They are also suited for quantitative identification of vegetation cover in terrestrial and shallow water systems.

The Isahaya Bay example demonstrates the capacity of orbital photographs to provide information on environmental change to the public with wide-ranging impacts on conservation. It also illustrates the value of historical imagery and long-term datasets such as the astronaut photography dataset. With approximately 375,000 images taken to date, older photographs serve as valuable references on the state of the environment over the last 30 years. In many cases, a suitable comparative photograph can be identified, even though the area was not a specific research target in the past. All the photographs from Gemini, the Space Shuttle and eventually from the International Space Station are maintained in a single World Wide Web database and can be searched simultaneously (Office of Earth Sciences 2000)

The example of elephants in Botswana illustrates an example of a population-level process that could be identified from orbit. Although effects of human populations on the landscape are the most visible population effects from orbit, certain impacts of other animal populations are also identifiable using image enhancement techniques. The particular image we employed (Figure 2, top) was taken with a 100 mm lens and represents moderate resolution compared to other NASA orbital photographs. Further applications using orbital photographs to examine large areas of vegetation disturbance would be fruitful. Patterns of clear-cut forestry in the tropical or temperate regions (e.g., Amazonia, the Pacific Northwest U.S., Siberia), and regeneration following hurricanes or fire would all be suitable studies. Image enhancement and

analysis techniques used with other types of remotely sensed images can also be applied to digitized astronaut photographs.

The most detailed example presented here, identification of seagrasses and mangroves, illustrates the potential for orbital photographs to be used for land-use classification in much the same way other remote sensing imagery is used. Our results compare favorably to seagrass classification studies using Landsat TM data at other locations (Luczkovich et al. 1993; Ferguson & Korfmacher 1997). Excellent results have been obtained for land use classification of coastal habitat types including mangroves (comparing Landsat TM and astronaut photography, Webb et al. in press). Improvements in optics of the orbital photography, and in image processing, are expected to help reduce the degree of misclassification and increase the overall accuracy of orbital photographs in ecosystem mapping and monitoring. This study was performed at a location where the seagrasses are mostly dense and visible at low tide. Many tropical locations support large areas of seagrass habitat of very low density or submerged in turbid water and unable to be reliably detected by any visual remote sensing technique, so ground surveys will always be necessary to monitor those habitats.

A major benefit of the orbital photographs is that they are economical enough to use for visual interpretation only, which is expensive with other remotely sensed imagery. Thus, scientists can use the images to get a general idea of a potential study area prior to field reconnaissance. Moreover, the images can be enhanced and visually interpreted using easy-to-use software such as Adobe Photoshop. This feature makes orbital photographs a highly useful source of qualitative data. This feature is available without researchers having to invest in expensive and complicated image analysis software. Thus, we strongly recommend that projects requiring any type of geographical representation of a potential survey area should consult the database of astronaut-acquired photography of Earth, regardless of the image-analysis capabilities of the individual scientists.

For quantitative applications, the availability of Internet-based search engines and file transfer of digitized images makes the imagery more accessible than ever before. PC-based

geographic information systems and image analysis programs make it possible for a number of scientists to apply these images to research questions in ways that would have been impossible just a few years ago. There have not yet been enough studies to delineate the research questions that can most easily be addressed using data from orbital photography. In general, we believe that applications suited to pixels of 8 m to 100 m (low contrast) in width are likely to be most suited to quantitative analyses.

Orbital photographs provide a continuing, non-commercial, and public-domain record of environmental changes over the last 30 years. As a data source, they can be combined using GIS with other soil or habitat maps, and even other remote sensing data. Orbital photographs can provide timely and important data for public information, guiding field surveys, and habitat classification, all of which are crucial for conservation biology and applied ecology.

Acknowledgments

Information and updates on the Fujimae Tidal flat area were provided by Atsuo Tsuji. Bussing and Nellis were supported during their research by the U. S. Agency for International Development. We would like to thank Ruth Allen for georeferencing the Shoalwater Bay photo, and Eleanor Sterling, Edward L. Webb and two anonymous reviewers for comments on the manuscript.

Literature Cited

- Anonymous 1996. Asia-Pacific Migratory Waterbird Conservation Strategy: 1996-2000. Wetlands International—Asia Pacific, Kuala Lumpur, Publication No. 117, and International Waterfowl and Wetlands Research Bureau—Japan Committee, Tokyo. Available at <http://www.biodiversity.environment.gov.au/bg/environm/wetlands/mwp/apstrat.htm> (last accessed 8 August 2000).
- Ben-Shahar, R. 1993. Patterns of elephant damage to vegetation in northern Botswana. *Biological Conservation* **65**:249-256.

- Ben-Shahar, R. 1996a. Do elephants over-utilize mopane woodlands in northern Botswana? *Journal of Tropical Ecology* **12**:505-515.
- Ben-Shahar, R. 1996b. Woodland dynamics under the influence of elephants and fire in northern Botswana. *Vegetatio* **123**:153-163.
- Briggs, J. M., and M. D. Nellis. 1991. Seasonal variation of heterogeneity in the tallgrass prairie: a quantitative measure using remote sensing. *Photogrammetric Engineering and Remote Sensing* **57**:407-411.
- Congalton, R. 1991. A review of assessing the accuracy of classification of remotely sensed data. *Remote Sensing of Environment* **37**:35-46.
- Coleman, T. L., M. D. Nellis, C. E. Bussing, M. Nkambwe, and S. Ringrose. 1996. Final Report USAID Grant No. PCE-5053-G-00-3044-00, Integrating Remote Sensing and GIS for Natural Resource Management in Botswana. Alabama A&M University, Normal, Alabama.
- Coles, R. G., W. J. Lee Long, and L. J. McKenzie. 1996. A standard for seagrass resource mapping and monitoring in Australia. In *Australian Marine Data Collection and Management Guidelines Workshop*, 5-6th December 1995, CSIRO Marine Laboratories, Hobart, Tasmania. Available from http://www.environment.gov.au/marine/manuals_reports/standards/general/coles.html (accessed 20 July 1999).
- Dennison, W. C., R. J. Orth, and K. A. Moore. 1993. Assessing water quality with submersed aquatic vegetation: habitat requirements as barometers of Chesapeake Bay health. *BioScience*. **43**:86-94.
- ERDAS, Inc. 1997. *ERDAS Imagine Field Guide*. ERDAS, Atlanta, Georgia.
- Ferguson, R. L., L. L. Wood, and D. B. Graham. 1993. Monitoring spatial change in seagrass habitat with aerial photography. *Photogrammetric Engineering and Remote Sensing* **59**:1033-1038.
- Ferguson, R. L., and K. Korfmacher. 1997. Remote sensing and GIS analysis of seagrass meadows in North Carolina, USA. *Aquatic Botany* **58**:241-258.

- Frazier, S. (editor). 1999. Directory of Wetlands of International Importance (CD-ROM). Wetlands International, Wageningen, The Netherlands. Available at http://www.wetlands.agro.nl/ramsar_database/ramsar.html (last accessed 8 August 2000).
- Hatcher, B. G., R. E. Johannes, and A. I. Robertson. 1989. Review of research relevant to the conservation of shallow tropical marine ecosystems. *Oceanography and Marine Biology Annual Review* **27**:337-414.
- Helfert, M. R., and K. P. Lulla, eds. 1989. Special Issue: Human-directed observations of the Earth from space. *Geocarto International* **4**:2-79.
- Herremans, M. 1995. Effects of woodland modification by African elephant *Loxodonta africana* on bird diversity in northern Botswana. *Ecography* **18**:440-454.
- Kashiwagi, M. 1998. Yuuryo-wa Umi-o Koete - Shuttle-ga mita Nihon-no Higata (Concern Spreads Over the Ocean - Japanese Tidal Flat as Seen from Space Shuttles) [In Japanese]. *SClaS (Science Asahi Magazine)* **1998.07.17**:80-81.
- Landgrebe, D., and L. Biehl. 1997. An introduction to MultiSpec© Version 7.97. West Lafayette, Indiana, Purdue Research Foundation. Available from <http://dynamo.ecn.purdue.edu/~biehl/MultiSpec/documentation.html> (accessed 26 May 1998).
- Lee Long, W. J., L. J. McKenzie, M. A. Rasheed, and R. G. Coles. 1996. Monitoring seagrasses in tropical ports and harbours. Pages 345-350 in J. Kuo, R. C. Phillips, D. I. Walker, and H. Kirkman, editors. *Seagrass biology: proceedings of an international workshop, Rottnest Island, Western Australia 25-29 January, 1996*. Faculty of Sciences, The University of Western Australia, Perth.
- Lee Long, W., L. McKenzie, and R. Coles. 1996. Seagrass studies in R. Berkelmans, editor. *Shoalwater Bay update: discovering the forgotten wetlands*. Reef Research **6** (Great Barrier Reef Marine Park Authority, Townsville, Queensland). Available from

http://www.gbrmpa.gov.au/corp_site/info_services/publications/reef_research/issue3_96/3wot.html (last accessed 8 August 2000).

Lee Long, W.J., L. J. McKenzie, and R. G. Coles. 1997. Seagrass communities in the Shoalwater Bay region, Queensland - Spring (September) 1995 and Autumn (April) 1996.

Queensland Department of Primary Industries Information Series QI96042, QDPI, Brisbane.

Luczkovich, J. J., T. W. Wagner, J. L. Michalek, and R. W. Stoffle. 1993. Discrimination of coral reefs, seagrass meadows, and sand bottom types from space: a Dominican Republic case study. *Photogrammetric Engineering and Remote Sensing* **59**:385-389.

Lulla, K., C. Evans, D. Amsbury, J. Wilkinson, K. Willis, J. Caruana, C. O'Neill, S. Runco, D.

McLaughlin, M. Gaunce, M. F. McKay, and M. Trenchard. 1996. The Space Shuttle Earth Observations Photography Database: an underutilized resource for global environmental sciences. *Environmental Geosciences* **3**:40-44.

McRay, B., J. Scott, and J. A. Robinson. 2000. Technical applications of astronaut orbital photography: how to rectify multiple image datasets using GIS. *Earth Observations and Imaging Newsletter*. Available online at <http://eol.jsc.nasa.gov/newsletter/gis/> (last accessed 8 August 2000).

National Research Council (U.S.). Board on Science and Technology for International Development. 1992. *Conserving biodiversity: a research agenda for development agencies*. National Academy Press, Washington, D.C.

Nedeltchev, N. M. 1999. Space Shuttle photography--a powerful tool of remote sensing investigation of human effects on the Earth. *International Journal of Remote Sensing* **20**:183-188.

Nellis, M. D., K. Lulla, J. M. Briggs, and C. E. Bussing. 1990. Interfacing geographic information systems and Space Shuttle photography for monitoring elephant impact in Botswana. *Papers and Proceedings of Applied Geography Conferences* **13**:10-15.

- Office of Earth Sciences, NASA-Johnson Space Center. 14 March 2000. The gateway to astronaut photography of Earth. Available at <http://eol.jsc.nasa.gov/sseop/default.htm> (last accessed 8 August 2000).
- Paulsson, B. 1992. Urban applications of satellite remote sensing and GIS analysis. The World Bank, Washington, D. C.
- Reilly, J. F., W. R. Muehlberger, P. W. Dickerson, H. H. Schmitt, and J. W. Young. 1998. Looking back at Earth. *Geotimes* **11**:14-20.
- Ringrose, S., S. Musisi-Nkambwe, T. Coleman, D. Nellis, and C. Bussing. 1999. Use of Landsat Thematic Mapper data to assess seasonal rangeland changes in the southeast Kalahari, Botswana. *Environmental Management* **23**:125-138.
- Ringrose, S., W. Matheson, F. Tempest, and T. Boyle. 1990. The development and causes of range degradation features in southeast Botswana using multi-temporal Landsat MSS imagery. *Photogrammetric Engineering and Remote Sensing* **56**:1253-1262.
- Robinson, J. A., B. McRay, and K. P. Lulla. 2000. Twenty-eight years of urban growth in North America quantified by analysis of photographs from Apollo, Skylab and NASA-Mir. Pages 25-41, 269-270 in K. P. Lulla, L. V. Dessinov, C. A. Evans, P. W. Dickerson, and J. A. Robinson, editors. *Dynamic Earth environments: new observations from Shuttle-Mir missions*. Wiley, New York.
- Russ, J. C. 1995. *The image processing handbook*, 2nd edition. CRC Press, Boca Raton, Florida.
- Suzuki, M. 1998. 21st Century committee questionnaire reveals "Worst 100 Wasteful Public Works Projects." *Japan Environment Monitor* **97-98**:8-15.
- Verlinden, A., and I. K. N. Gavor. 1998. Satellite tracking of elephants in northern Botswana. *African Journal of Ecology* **36**:105-116.
- Webb, E. L., Ma. A. Evangelista, and J. A. Robinson. Digital land use classification using Space Shuttle acquired Earth Observation Photographs: a quantitative comparison with Landsat TM imagery of a coastal environment, Chanthaburi, Thailand. *Photogrammetric Engineering and Remote Sensing*. In press.

Wobber, F. J. 1969. Orbital photographs applied to the environment. *Photogrammetric Engineering* **35**:852-864.

Frazier, S. (editor). 1999. *Directory of Wetlands of International Importance* (CD-ROM). Wetlands International, Wageningen, The Netherlands. Available at http://www.wetlands.agro.nl/ramsar_database/ramsar.html (last accessed 8 August 2000).

Table 1. Supervised classification performance for digitized astronaut photograph of Shoalwater Bay, Queensland, Australia, 17 April 1985 (percent and number of pixels).

Class	Entire Image Classified			With Upland Excluded ^a	
	Training Accuracy	Test Accuracy	Misclassified as ^b	Test Accuracy	Misclassified as ^b
Clouds	97.2% (886)	94.6% (129)		93.5% (77)	
Water	83.2% (16242)	93.1% (3509)		92.6% (3509)	
Seagrass	80.3% (1433)	84.3% (345)	Sediment, 12.7%	43.8% (345)	Sediment, 38.3%
Sediment	26.7% (664)	11.3% (248)	Seagrass, 85.1%	61.7% (248)	Seagrass, 28.2%
Land	77.4% (5626)	76.9% (1657)	Mangrove, 22.0%		
Mangrove	51.6% (1628)	59.8% (640)	Land, 34.5%	93.5% (613)	
Total	78.9%,	82.2%,		87.6%	
Kappa statistic		66.0%		78.7%	
Kappa variance		0.0046		0.0048	

^aSee details in text. Number of pixels differ for some categories because of test fields that were within the area eliminated by the shoreline mask.

^bPrimary misclassification categories are presented for cases > 10%.

Figure 1. Reclamation of the Isahaya Bay tidal flat off of the Ariakekai, Japan, as seen from the Space Shuttle. Both images are enlarged details of a more extensive photograph and the later image is much more enlarged than the earlier image. Images have been rotated and scaled to facilitate comparison. Arrows indicate the area within Isahaya Bay before and after the dike was constructed. NASA photographs left, STS034-78-048, 20 October 1989; right STS090-739-079, 27 April 1998.

Figure 2. Top: The Chobe River area, Northern Botswana, detail of a more extensive photograph and a portion of the Chobe District study area (NASA photograph STS008-33-993, September 1983). Bottom: Unsupervised image classification. White areas were predicted to have higher levels of elephant impact. Regions of verified elephant vegetation damage are marked by letters.

Figure 3. Top: Shoalwater Bay, Queensland (NASA photograph STS51D-45-63, 17 April 1985). Bottom: overlay of the summary map of seagrass meadows (black lines) and mangroves (gray shading; Lee Long et al. 1996), and the classification results for the complete image. In this analysis species-specific information on seagrass composition (indicated by different black bar patterns) was not considered.

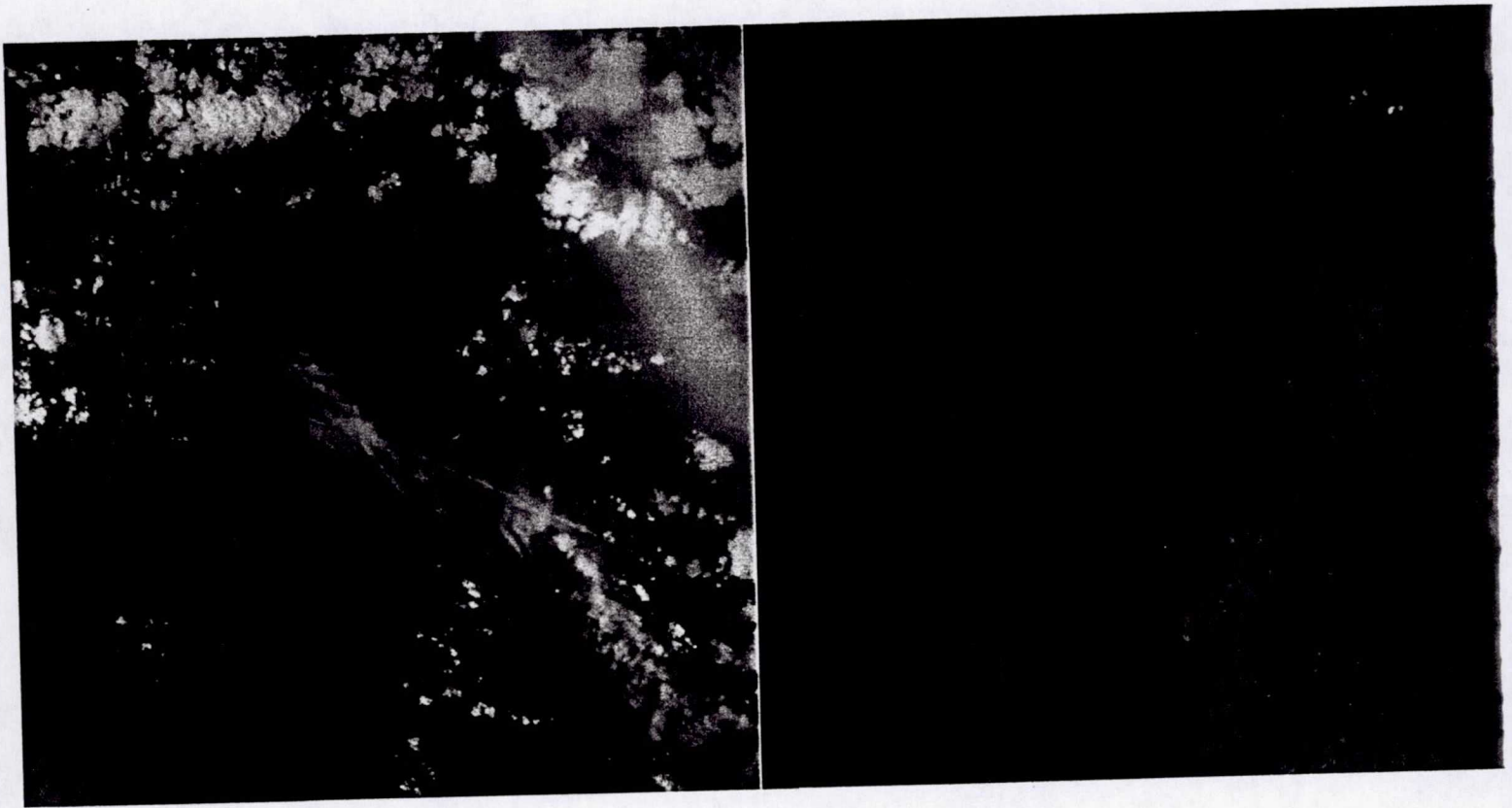


Fig 1

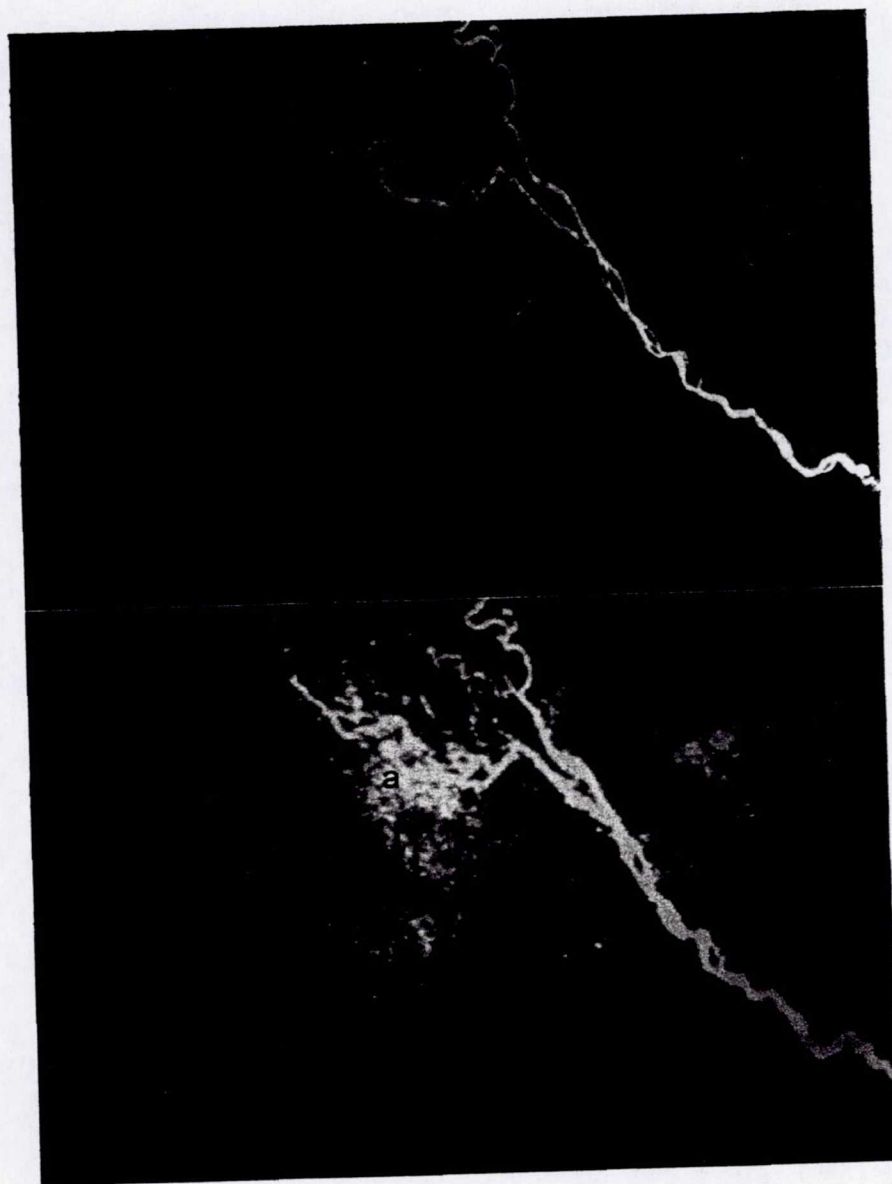


Fig 2



Fig 3